# Modelling hydraulic, sediment transport and slope processes, at a catchment scale, using a cellular automaton approach.

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*Presented at the second annual conference of GeoComputation '97 & SIRC '97,*
*University of Otago, New Zealand, 26-29 August 1997*

## *Abstract.*

There have been recent advances in the numerical modelling of hydraulic and sediment transport processes at a fine scale, but the ability to extrapolate these advances to a larger scale is rarely realised. Existing approaches have been based upon linked cross sections, giving a quasi 2-d view, which is able to effectively simulate sediment transport for a single river reach. A catchment represents a whole discrete dynamic system within which there are channel, floodplain and slope processes operating over a wide range of space and time scales. A Cellular Automaton (CA) approach has been used to overcome some of these difficulties, in which the landscape is represented as a series of fixed size cells. At every model iteration, each cell acts only in relation to the influence of its immediate neighbours in accordance with appropriate rules.

The model presented here takes approximations of existing flow and sediment transport equations, and integrates them, together with slope and floodplain approximations, within a cellular automaton framework. This method has been applied to the Catchment of Cam Gill Beck (4.2 km$^2$) above Starbotton, upper Wharfedale, a tributary of the River Wharfe, North Yorkshire, UK.

This approach provides for the first time a workable model of the whole catchment at a meso scale (1m). Preliminary results show the evolution of bars, braids, terraces and alluvial fans which are similar to those observed in the field, and indicates the emergence of significantly non-linear behaviour.

## *Introduction*

Fluvial sediment transport and the supply of sediment to and from the floodplain are the most important processes in the evolution of a catchment. For this and other reasons, fluvial models, operating at a variety of scales, have taken a precedence in geomorphology. These range from the three dimensional modelling of circulation surrounding a confluence, detailed two dimensional finite element grids of water surface profiles (Nicholas 1997, Bates et al 1997) and the more 'classic' one dimensional approach of calculating over cross sections, such as HEC II. Most appear successful, but due to the complexity of solving the complex Navier-Stokes equations used, are computationally restricted to operating in a confined area. They also fail to account for processes outside of this study reach, such as mass movement, hydrology and changes in upstream sediment supply.

Other authors, Howard (1994, 1996), Polarski (1997) take a different approach, placing the emphasis on the slope processes. Howard simplifies channel operations to a sub grid cell process, with values for width and depth calculated using empirical relationships. This approach allows the aggradation and degradation of the channel, in the context of the whole catchment, but does not allow the formation of terraces, a flood plain stratigraphy, or differing channel forms which geomorphologists use to interpret past environmental change.

Whilst both of these approaches are fruitful, the former, hydraulic approach trades catchment scale realism for local flood plain accuracy, whereas the latter sacrifices channel accuracy for realism at the catchment scale. Two reasons for this split can be identified. Firstly, numerical flow modelling mainly comes from a strongly engineering background, where the prime consideration is the channel. The second reason is scale.

When examining a topic as complex as landscape evolution, there are numerous processes acting over a wide range of time and space scales. These range from the movement of a pebble in a split second, to the creep on a mountainside over thousands of years. The importance of a mass landslide in changing the landscape is obvious, but should we ignore the pebble's movement? If we assume our landscape to be a chaotic system, highly sensitive to initial conditions, then the pebbles' action is important, as is the butterfly effect to a climate modeller. Lane et al (1997) seems to confirm this idea, suggesting that fluvial system behaviour is highly dependant upon its context. This presents a major problem for a modeller in selecting an appropriate level of resolution. For example, if studying the Rhine Basin, how far should we account for the turbulence generated by the movement of a 5mm clast? In principle the answer is not clear, as there are critical moments when it influences the outcome, but in practice computational limits effectively exclude such a high level of detail.

Incorporating small scale processes in a catchment model is troublesome, because of these scale ranges. The computationally intensive nature of finite element methods makes their use impracticable over the long timescale that slope influences require (>1000 years), and it is similarly impossible for them to provide models for the full spectrum of flood events. Furthermore, over the course of a flood, catchments are spatially dynamic. Stream heads may extend, new tributaries and channels may form. For hydraulic modelling this creates numerous problems, as changes in bed/floodplain topography and spatial changes in the network require a frequent re-definition of the mesh of nodes used, which is highly time consuming, especially if a curvilinear approach is used.

In this paper, a cellular automaton (CA) model, simple in concept yet complex in implementation, is applied to an entire small upland catchment. This model aims to reconcile scale issues by dividing the catchment into uniform 1m $^2$ grid cells. This resolution is chosen as being small enough to allow representation of fluvial processes, yet large enough to encompass a whole catchment. Furthermore, to resolve temporal scale problems a variable time step is used which is dependant upon the erosion rates. This allows the representation of small scale processes such as fluvial erosion, yet incorporates the long term effects of vegetation change and soil creep. This model is being developed as part of on-going research to investigate the relative effects of climate change and humans influence on the upland landscape over the Holocene (Coulthard *et al* 1996, 1997, Macklin & Lewin 1993). In this paper the Authors wish to :

1. Focus on the models unique application at this scale.
2. Investigate examples of non linear behaviour in the relationships between processes.
3. To consider an appropriate choice of scale, for models of environmental change.

## *Method.*

The model is applied to the catchment of Cam Gill beck, a tributary of the River Wharfe, above the hamlet of Starbotton, North Yorkshire, UK. The CA method used and details regarding its implementation are described in full by Coulthard *et al* (1996, 1997) but sumarised below.

The catchment was digitised from 1:10 000 scale Ordnance Survey map contours. This data, with additional EDM surveyed detail for the valley floor was combined using the TOPOGRID command in ARC-INFO to create a 1 m$^2$ resolution DEM, of 4.2 million points (figure 1.). Within this topographic representation, each grid cell has properties of elevation, discharge, vegetation, water depth, and grainsize. For every model iteration, these values are altered in accordance only to their immediate neighbour and four sets of processes. The first component is a model of hill slope hydrology, using an adaptation of TOPMODEL (Beven & Kirkby 79) with an exponential soil moisture store. The second input is a hydraulic routing scheme, utilising bed slope and calculating depth with an adaptation of Mannings formulae. Thirdly, fluvial erosion and deposition using the Einstein-Brown (1950) equation, applied to five different grainsize fractions incorporated with a 3 strata active layer system similar to that used by Parker (1990) and Hoey & Ferguson (1994). Finally, mass movement rates are calculated, incorporating a factor of safety which changes with the soil saturation.

Two main scenarios have been applied to the model. Firstly fifteen floods of equal magnitude, equivalent to a bankfull discharge have been simulated, to show cumulative changes in sediment discharge and morphology. Secondly, a larger flood approximating to a 5 year flood event was simulated.

## *Results.*

Figure 2 shows the results of running 15 floods of approximately bankfull discharge through the upper part of the catchment. This graph shows two values, firstly the amount moved in each flood and secondly the amount removed from the catchment. The initial conditions were with an 'untouched' catchment where every cell had the same grainsize content. This meant that for the first few runs large amounts of material were removed because the channel was armouring itself from these initial conditions and had a high sediment availability. Subsequent to this peak, the catchment displays a non linear pattern of behaviour, with unrelated peaks in the sediment discharge. This may be attributed to the movement of 'slugs' (Nicholas *et al* 1995) of sediment down stream, and the consequent remobilisation of these, in later floods. These peaks in activity can be also be linked to the input of landslides. Mass movement producing an input of fines into the system. When monitoring the model's operation, the activity in the catchment corresponds to that of the hydrograph. Little happens until the peak of the hydrograph occurs then there is a flurry of activity as sediment is mobilised. This then decreases with the falling limb. There are however episodes of activity during fairly low flow times. This is again attributed to the input of mass movement from the slopes.

Figures 3 to 6 show the confluence section as indicated in Figure 1. These show the confluence of the main two upland channels. Figure 3 shows the 'initial conditions of the area, where a small discharge has been run down the catchment, resulting in the definition and formation of channels. Figure 4 shows the same region after the 16 floods outlined in Figure 2 above. Figure 5 shows again the same area, but after 1 large flood of approximately 5 year return interval. These three views show the activity of several processes. The floods have led to the development of a 'fan' like structure at the base of the right hand tributary, produced by fines from the upland areas. This has caused the widening of the channel opposite and downstream. A multiple channel has formed here, due to the large sediment influx, the channel diverging and converging. Figure 6 corroborates these observations, showing the grainsize distribution for the section after the 16 floods. This shows an 'armouring' down the centre of the multiple channels and a 'glut' of fine material deposited at the base of the fan.

Figures 7 a & b, show two plan-views of one small section of 80 by 30m, as outlined on Figure 1 . Flow is from top to bottom. On the right are four cross sections corresponding to the sections on the grainsize chart. This is a lower part of the channel seen after the 16 floods mentioned above. Here, two distinctly different formations have occurred. In the upper two sections, the flow emerges from a narrow constrained section into a wide valley floor. Consequently there has been deposition, with the formation of a coarse deposit on the right side. 30m downstream, where the system is eroding, removing the deposits from above, the opposite has occurred, where there is a fine deposit on the left of the channel. These features are very similar to a 'boulder berm' and side bar / terrace, in both

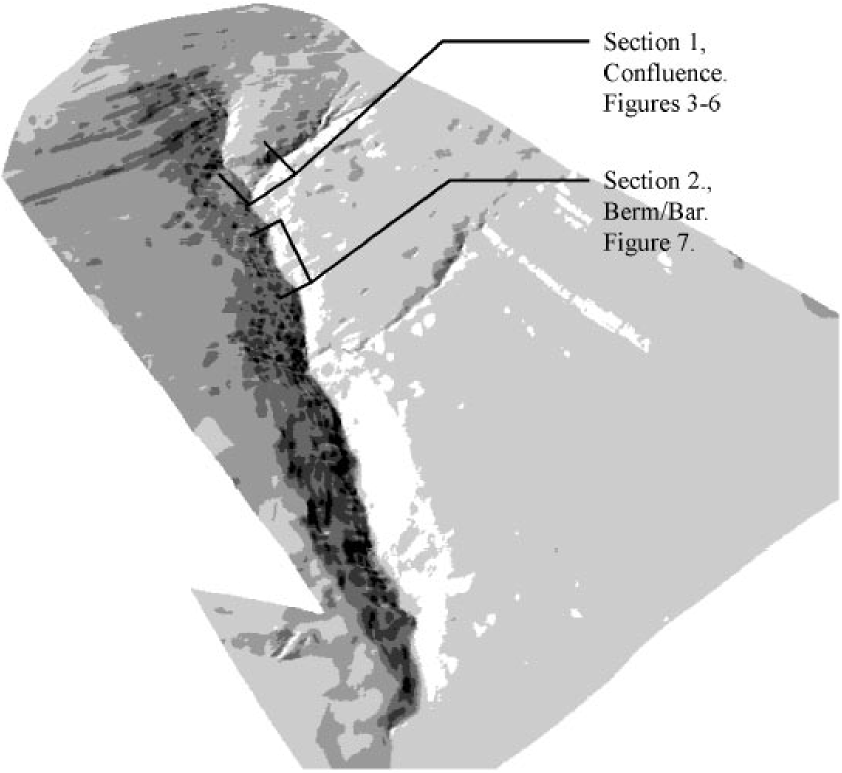

*Figure 1. Draped image of Starbotton DEM. Scale 1600 by 2800m.*

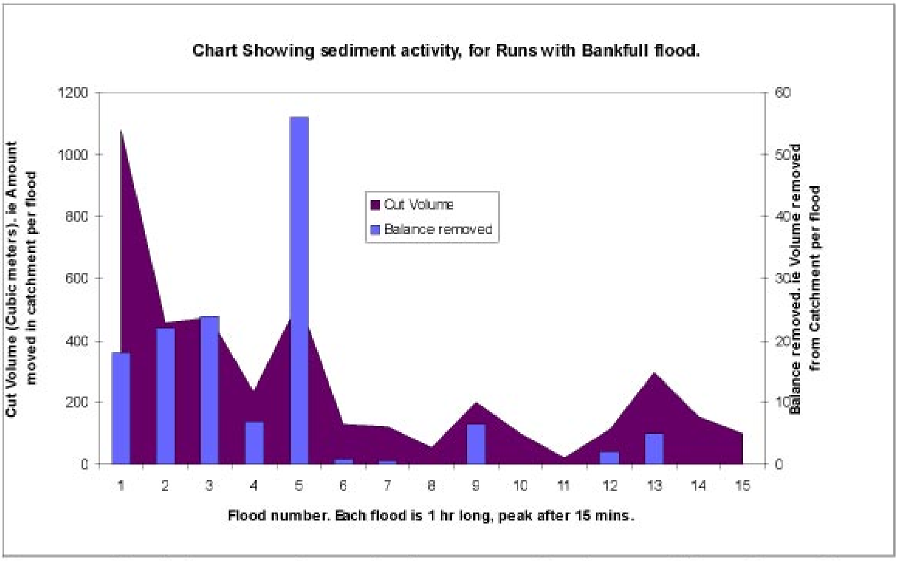

*Figure 2. Graph showing volume of sediment moved and removed from the catchment for each flood.*

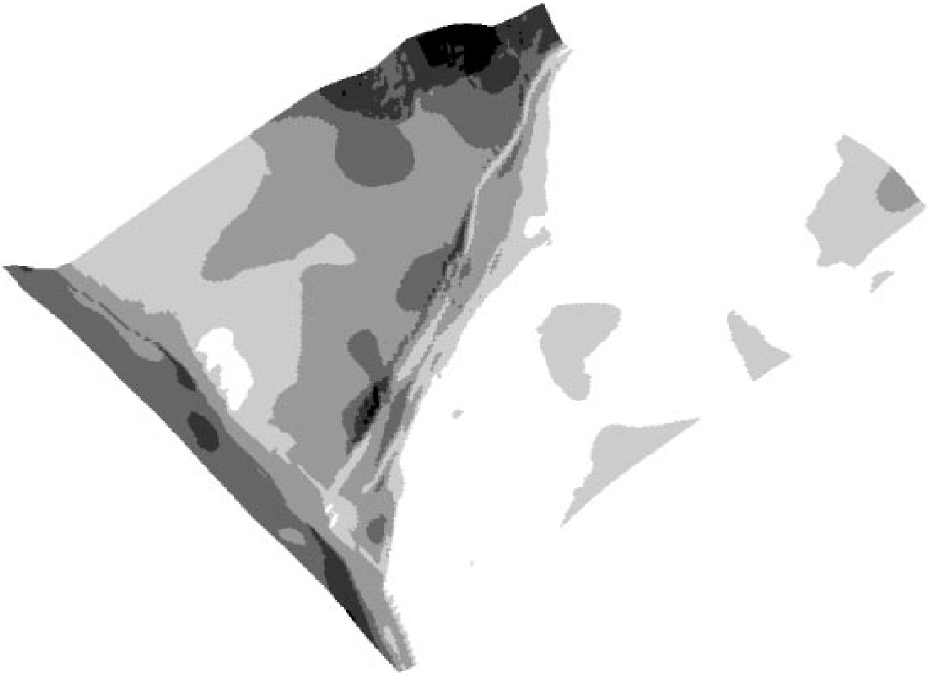

*Figure 3. Confluence section before flood series.*

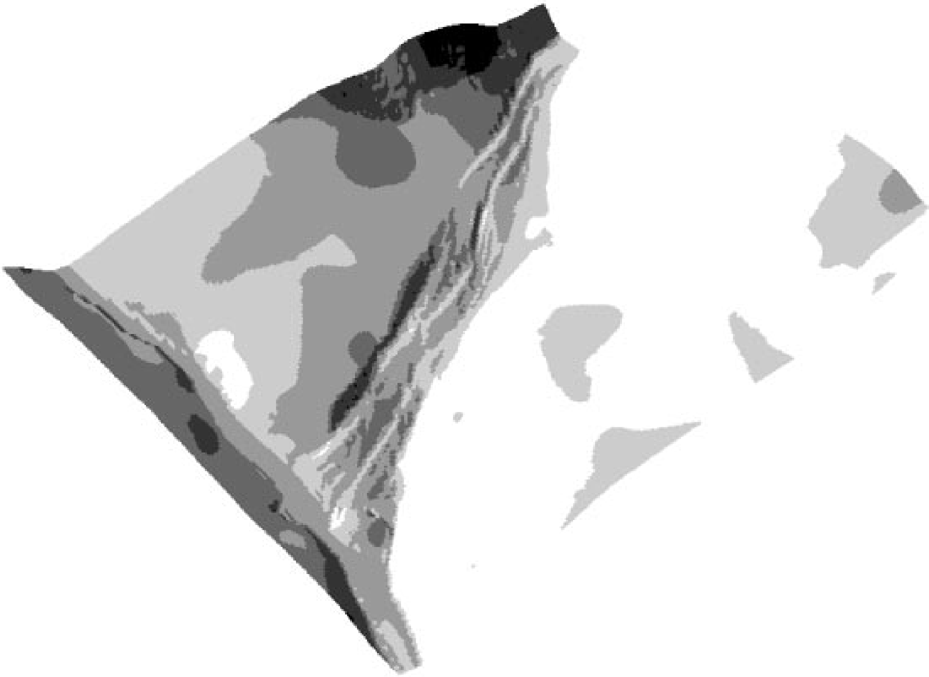

*Fig 4. After 16 floods of bankfull discharge.*

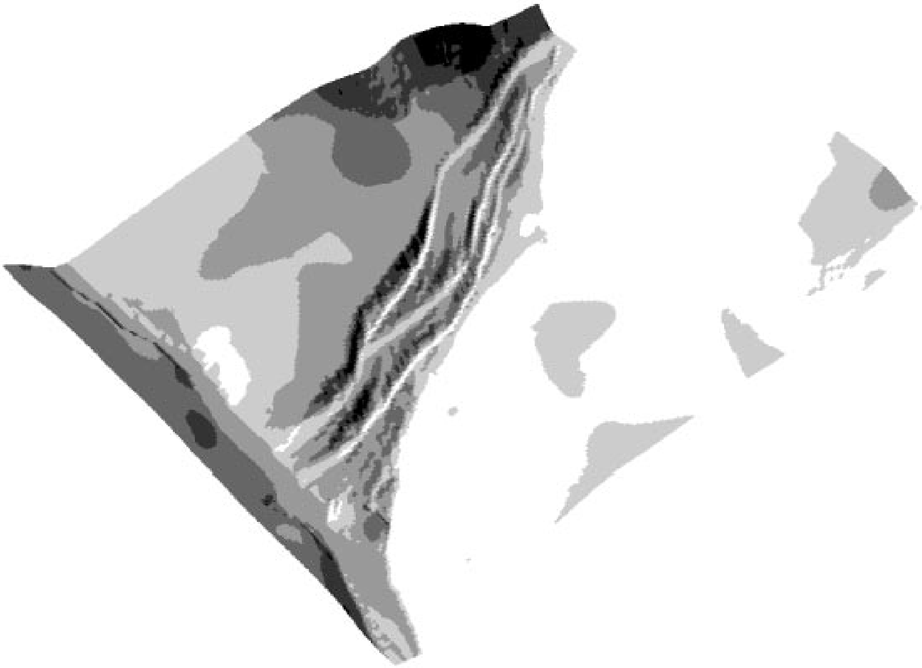

Figure 5. After a '5 year' flood event.

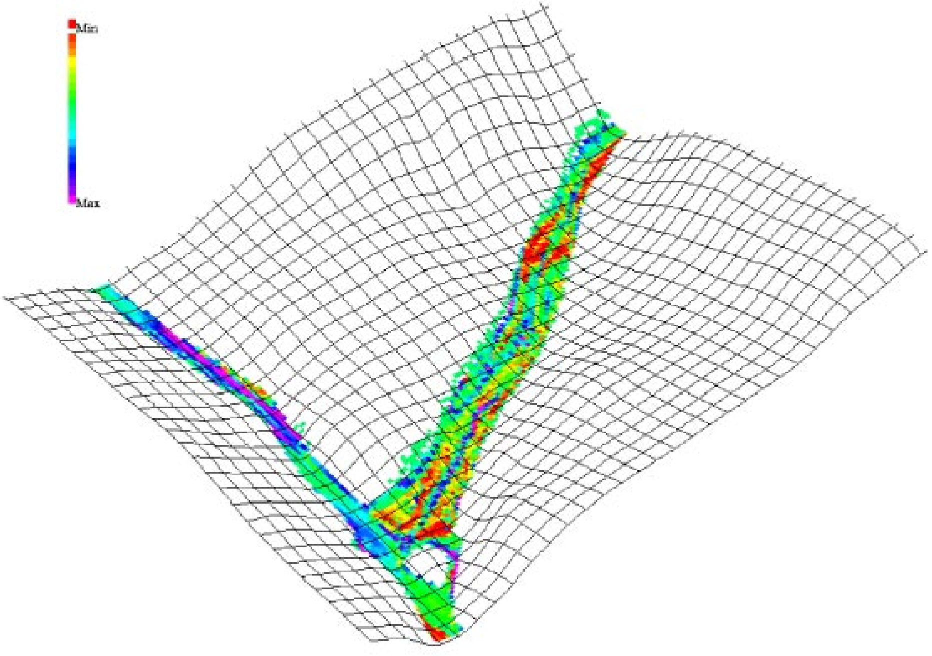

Figure 6. Grainsize Composition of confluence section.

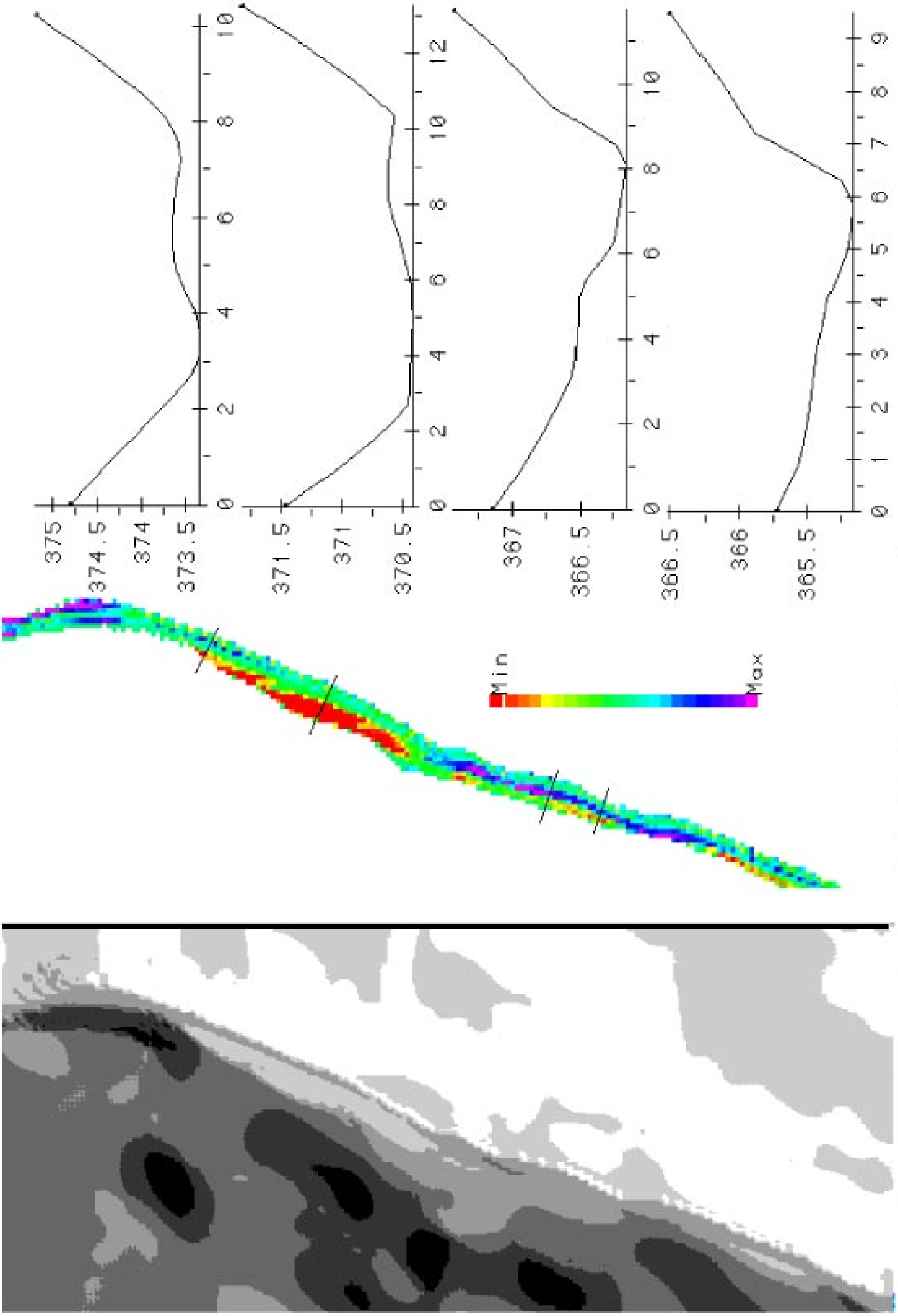

Figure 8. Section 2, showing plan view of shaded relief, Grainsize and four cross sections.

their planform and morphology. Although this is only a preliminary run of the model, a brief field recconaisance shows a high correlation in both location and morphology.

## *Discussion.*

Observations of catchment dynamics show many examples of non linear behaviour, from the hydrograph output to sediment discharges (Lane *et al* 1997, Evans 1996). The model depicts similar behaviour, with an unpredictable sediment discharge, showing a partial decoupling between the hydrograph and sediment transport processes. Obviously there cannot be much sediment transport without a flood, but a flood does not pertain to sediment transport. The initial runs of the model, as described above, show the formation of landslides, berms, bars, braids, terraces and alluvial fans, of similar magnitude and form to those observed in the study area. These have all 'evolved' over the 15 floods, the model starting with featureless valley floors, equal initial conditions and distributions of sediment. The behaviour and formation of these features is all symptomatic of non linear behaviour. The grainsize distribution in figure 6 is a good example, with fines in areas of lower slopes where sediment has collected and armouring in the channels. Throughout the 16 runs of the model, there is a constant interaction between the channel and these stores, being re-mobilised and dispersed on some floods, yet left on others. The braided patter observed in figures 4 and 5 again is a result of these nonlinearities. The planform is constantly shifting, channels growing in one area, yet declining in another.

The model shows chaotic tendencies in its sensitivity to initial conditions. When the elevation data is saved to file, the values are truncated to 6 decimal places. When the data is re-loaded and the model run, different results emerge from when the values are retained in the computer memory at their full length.

Are these complex responses simply a condition of the models design? What happens to this response if more processes are integrated, such as a better hydrological model, or slope representation? Initial sensitivity testing hints that whilst altering the laws used gives different results, they are very similar. For example with figure 7, if this is run with a different sediment transport law, the exact dimensions of the berm / terrace sections is different, but their form and location is the same. Computational instabilities could explain non linear outputs, but to maintain stability, the amount eroded or deposited between each cell is limited to within a few percent of the local slope.

The implications of a model generating such a non linear response are considerable. We cannot rely upon a simple regression style model, because the response of the system is complex. The spatially distributed nature of the system means that we have to account for processes throughout the catchment. It is not the 'random' input from weather systems that is solely responsible for the non-linear behaviour of our fluvial systems, there is an inherent chaotic instability within the whole system. This is further demonstrated by the models sensitivity to initial conditions. Unfortunately, most fluvial modelling schemes, fail to account for non linear behaviour in any form.

If a catchments behaviour is unstable, sensitive to small perturbations in initial conditions, how can we incorporate changes that are so small to appear inconsequential, yet may prove to be important? Paola (1996) treats a 'whole' braided river system as a stochastic one, and finds the addition of a random element contributes to the accuracy of estimates of total flow and sediment flux. However, a chaotic system whilst appearing to give stochastic response is in fact deterministic. The LAB (Bridge & Leeder 1979)model of alluvial architecture is driven by an avulsion frequency, derived from a probability distribution around an observed mean. Whilst there are many other limitations to their approach (Heller & Paola 1996) similar approximations may represent one answer. Another approach may take the form of an AI answer, such as a fuzzy logic application or 'training' a neural net to incorporate this chaotic element. However, we may never get a true deterministic answer, having to rely upon an average of model runs, as climate modellers do.

The model highlights the importance of mass movement and slope processes in the evolution of a small catchment.

Disabling the landslide module resulted in a partial reduction in the non linearity. This suggests that the input from channel banks and heads is important, both as a sediment input and trigger for erosion/deposition episodes. Analysis of cut fill sequences, shows stream heads to be major contributing areas, as producers of sediment. This re-inforces research claims by Kirkby (1994) regarding the importance of the stream head in a networks evolution. There is still some non linear sediment response even when the mass movement section is removed, and this demonstrates the re-mobilisation and dispersal of sediment through out the catchment is also an important aspect of the systems behaviour. For example, the deposition of a clast may result in the lateral migration of the channel towards a pre-existing deposit, re-mobilising fresh material. In contrast to these positive feedbacks, there are several negative ones, controlling or pacifying the models operation. For example at the base of figure 7, where the channel has cut a terrace, incision is resulting in a stable channel pattern.

By choosing the 1m $^2$ scale, the effects of catchment scale processes such as hydrology and slope processes can be studied, as well as incorporating smaller scale catchment dynamics such as the in channel storage and re-mobilisation of sediment. This provides a clear advantage over models in which separate slope and channel modules are coupled together. With these schemes, different spatial and time scales have to be resolved and feedback's have to be explicitly defined. Furthermore, by selecting a 'meso' scale, this model demonstrates synergistic behaviour, showing that the overall catchment behaviour cannot be simulated simply from the sum of its individual component processes.

## *Conclusions.*

Non linearities in catchment systems are crucially important at all scales, and we will never be able to fully account for all of them. It is not practical for large basin scale models to simulate three dimensional flow around clasts, yet the broader impact of such small scales must be incorporated. Similarly, three dimensional coupled flow and sediment transport models will have to account for irregularities in the time and space distribution of the arrival of sediment from upstream. Ultimately, the accurate incorporation of such factors will determine the power of our next generation of geomorphological models. Given the increases in computer power and advances in modelling techniques, it may prove that these 'chaotic' terms are the most important.

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